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Opportunities for sustainable intensification in European agriculture

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ABSTRACT

Sustainable agricultural intensification is needed to tackle food insecurity and global environmental change. Local environmental conditions determine the needs and potentials for increasing sustainability of agricultural practices. However, the potential for implementation also depends on socio-economic factors, as farmers need to adopt innovative farming practices, and consumer demand affects the economic feasibility. This study aims to map opportunities for sustainable intensification in Europe taking into account farmer characteristics, consumer behaviour, environmental pressures, and unexploited agronomic potentials. In areas identified as having high opportunities, we estimate the impacts of specific sustainable intensification measures on both intensification (in terms of calorie gains) and sustainability (in terms of resource savings). The study finds high spatial variation in opportunities for sustainable intensification across Europe. High opportunities for sustainable intensification are found on 34% of the arable area in Europe. In addition, the analysis shows that a combination of different measures can simultaneously improve food security and sustainability.

1. Introduction

Achieving global food security becomes increasingly challenging. On the consumer side, population grows and changes its consumption patterns. On the production side, increasing food production is limited by land availability for agricultural expansion and trade-offs related to intensification. According to medium estimates, cropland could potentially expand to less than double (a factor of 1.0–1.9 of) its size in 2005 (Eitelberg et al., 2015). This compares to a slightly higher projected increase (a factor of 1.6–2.0) in food demand in terms of calories until 2050 (Tilman et al., 2011; Valin et al., 2014). However, land assigned as 'available' is in reality already providing multiple functions besides food production (Verburg et al., 2013), such as the production of feed, fibre, fuel and timber, regulating ecosystem services like carbon sequestration, water purification and flood control, and habitat provision for flora and fauna. Furthermore, potentially available land is likely to be less productive than current agricultural areas. Therefore, recent increases in food production were attained by intensification rather than expansion (Foley et al., 2011). In spite of this intensification, there are still considerable yield gaps in many parts of the world (related to the efficiency within one crop cycle) (Mueller et al., 2012; Pradhan et al., 2015) as well as harvest gaps (related to the cropping frequency) (Ray and Foley, 2013; Yu et al., 2017) that could be closed.

However, intensification is often attained at the expense of environmental integrity. Most importantly, irrigation and fertilization drive water scarcity (Scherer and Pfister, 2016a), eutrophication (Scherer and Pfister, 2015a), and acidification (Tian and Niu, 2015). In some views, environmental sustainability and intensification seem incompatible and contradictory (Robinson, 2004; Garnett et al., 2013). That is why, in the past, nature protection was typically striven for by setting apart lands as protected areas (Mace, 2014). Such a strategy, however, cannot avoid the negative impacts of intensively used agricultural areas. Moreover, it is increasingly recognized that, in a human-dominated world, people and nature are interdependent and their demands must be tackled simultaneously (Mace, 2014). Consequently, many scientists emphasise the need for sustainable intensification of agriculture (Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011; Smith, 2013). Ideally, sustainable intensification implies more production on the same land area while reducing environmental impacts and maintaining ecosystem functioning. Pathways to sustainable intensification can be diverse and must be adapted to the location and context (Garnett et al., 2013; Buckwell et al., 2014). Measures range from agronomic development (e.g. no-tillage farming) and resource-use efficiency (e.g. deficit irrigation) at the farm scale to land use allocation (e.g. spatial targeting) and regional integration (e.g. diffusion of innovation) at the regional scale (Weltin et al., submitted). Trade-offs between intensification and sustainability may be unavoidable and, therefore, yield increases are not imperative to the concept. Instead, the concept of sustainable intensification can include conventional intensification at some locations and de-intensification or land

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reallocation at other locations in favour of environmental benefits. Still, overall output and sustainability over larger scales should increase without agricultural expansion (Garnett et al., 2013; Buckwell et al., 2014).

Studies related to sustainable intensification mostly focus on quantifying the opportunities of increasing production (Mueller et al., 2012). However, others have indicated that meeting the twin challenge of sustainable intensification would also require changes on the demand side (Foley et al., 2011; Smith, 2013; Davis et al., 2016a). Looking at the opportunity space from a demand and a supply perspective simultaneously is rarely done, with the notable exception of Pradhan et al. (2014). This study aims to map opportunities for sustainable intensification in Europe by considering both socio-economic and environmental factors. We focus on arable farming while acknowledging that similar challenges apply to pastoral farming. Europe is among the most densely populated world regions (Doxsey-Whitfield et al., 2015) and, as a result, faces a high land pressure. At the same time, Europe is rich in productive farmland and is among the largest food importers as well as exporters (Benton et al., 2011). The global importance of Europe as a consumer and producer makes it a relevant focus area for our study. Agriculture in Southern and Eastern Europe can still be intensified, while agriculture in Northern and Western Europe is already intensive (Pradhan et al., 2015). Still, the latter can improve sustainability and manage food demand. Next to determining areas of high opportunities, the objective of this study is to provide the first coarse estimate of the potential benefits of a set of measures for both agricultural production and sustainability in these areas.

2. Methods

2.1. Conceptual framework

The feasibility of sustainable intensification of crop production in Europe depends on both (1) socio-economic opportunities (Section 2.2) as the willingness of farmers and consumers to produce and buy sustainably intensified agricultural products, and (2) environmental opportunities (Section 2.3) as the necessities for reducing environmental impacts (e.g. water scarcity) or the existence of unexploited potentials (e.g. harvest gaps). After mapping the individual indicators for both types of opportunities across Europe, they were aggregated to obtain overall indices for socio-economic and environmental opportunities, respectively, following the aggregation procedures described in Sections 2.2 and 2.3. The opportunities of both aspects were mapped by means of an opportunity matrix for colour coding. The indicators were classified as low, moderate, or high if they are i) below the quantile Q_{25}, between Q_{25} and Q_{75}, or $> Q_{75}$ (default), or ii) below the quantile $Q_{33.3}$, between $Q_{33.3}$ and $Q_{66.7}$, or $> Q_{66.7}$ (alternative). Since there is considerable uncertainty in the choice of indicators and associated spatial data, we judged such a quantile representation as adequate for the type of information rather than more precise quantitative details. A special case is food waste, whose reduction at the consumption level is independent of the location of agricultural production and the behaviour of farmers. Therefore, only opportunities by consumers were considered in this case.

Within areas of the same identified opportunity category, the second part of the analysis aims to quantify the effects of implementing a set of sustainable intensification measures on (1) intensification in terms of calorie gains (or losses), and on (2) the environment in terms of resource savings (Fig. 1). For each measure, both aspects are considered. Due to the higher implementation feasibility, we emphasize areas with high opportunities with regards to both the environment and socio-economic characteristics as well as for areas with high opportunities with regards to one and moderate opportunities with regards to the other aspect. By not focusing on only high opportunities in both aspects, the effects of implementing sustainable intensification can be assessed more widely. As a reference for the analysis, we use the year 2010. When data for the reference year were not available, we used data closest to the reference year, with preference given to the more recent year (i.e. rather 2011 than 2009).

Due to the multitude of global environmental challenges (Steffen et al., 2015) and pathways towards sustainable intensification (Weltin et al., submitted), it is unfeasible to analyse all possible environmental opportunities and measures at continental scale. We focus on the three most vital resources: land (Eitelberg et al., 2015), water (Scherer and Pfister, 2016a), and soil (Keesstra et al., 2016). These resources are not only vital for ecosystems, but are also limiting for agricultural production providing food to humans. Like challenges and pathways, the determinants of pro-environmental behaviour are numerous and complex (Bamberg and Möser, 2007) and were, therefore, simplified based on the best information available. By balancing the available information and the complexity of modelling, this study aims to provide an overview of opportunities for sustainable intensification in Europe. It illustrates the potential for sustainable intensification and points to priority areas for more detailed assessments.

2.2. Socio-economic opportunities

To map socio-economic opportunities for sustainable intensification, we used spatial proxies for the adoption of innovation and sustainable practices among farmers and consumers, derived from a literature review. Farmers open to innovation and sustainability tend to be younger, be better educated and have larger farms (Genius et al., 2006; Passel et al., 2007; Koesling et al., 2008; Lobley et al., 2009; Gómez-Limón and Sanchez-Fernandez, 2010; Zagata and Sutherland, 2015; Degla et al., 2016; Pavlis et al., 2016). The type of tenure is important because farmers tend to adopt more sustainable practices on owned land than on rented land (Fraser, 2004; Kassie et al., 2015). If farmers own the land, they are more willing to invest (Kabubo-Mariara, 2007) and to participate in agri-environmental schemes (Walford, 2002).

Besides the role of consumers for demand-side measures, consumers might also influence farmers either through vendor-customer interactions (Hunt, 2007) or through social norms within the society (Fehr and Fischbacher, 2004) both belong to. Among consumers, potential for pro-environmental behaviour (including consumption) was found to be associated with various character traits and behaviours. First, post-materialistic attitudes favour pro-environmental behaviour (Inglehart, 1995; Franzen and Meyer, 2010; Salonen and Åhlberg, 2013). Post-materialism refers to a change of values emphasizing material needs and luxuries to emphasizing self-expression and life quality (Inglehart, 1995). Second, although environmental concerns might not be the main motivator to purchase organic food (Hughner et al., 2007; Kriwy and Mecking, 2012) or to be a vegetarian (Fox and Ward, 2008; Hoffman et al., 2013), both types of consumers still demonstrate pro-environmental attitudes. We used organic sales and a low or decreasing consumption of meat as proxies for the relative share of such consumers. Third, we approximated pro-environmental attitudes by affiliations with environmental NGOs and agreement to hypothetical donations for the environment.

The data sources for the parameters mentioned above are described in Table 1. Eurostat data (EC, 2016) are given as ordinal variables. In absence of more detailed information, the class reflecting the highest opportunity was assigned the value 1, while the class reflecting the lowest opportunity was assigned the value 0. Where only one additional categorical class exists, it was assigned the value 0.5. Where several other interval classes exist, the values were scaled between 0 and 1 depending on the mid-range value of the class compared to the two boundary values (Table A1-A4 in the Appendix). The continuous variables describing consumers were scaled to range from 0 to 1 based on their minima and maxima. In addition, pairwise Pearson correlation analysis were carried out to support the interpretation of the results.

In an intermediate step, socio-economic parameters were averaged

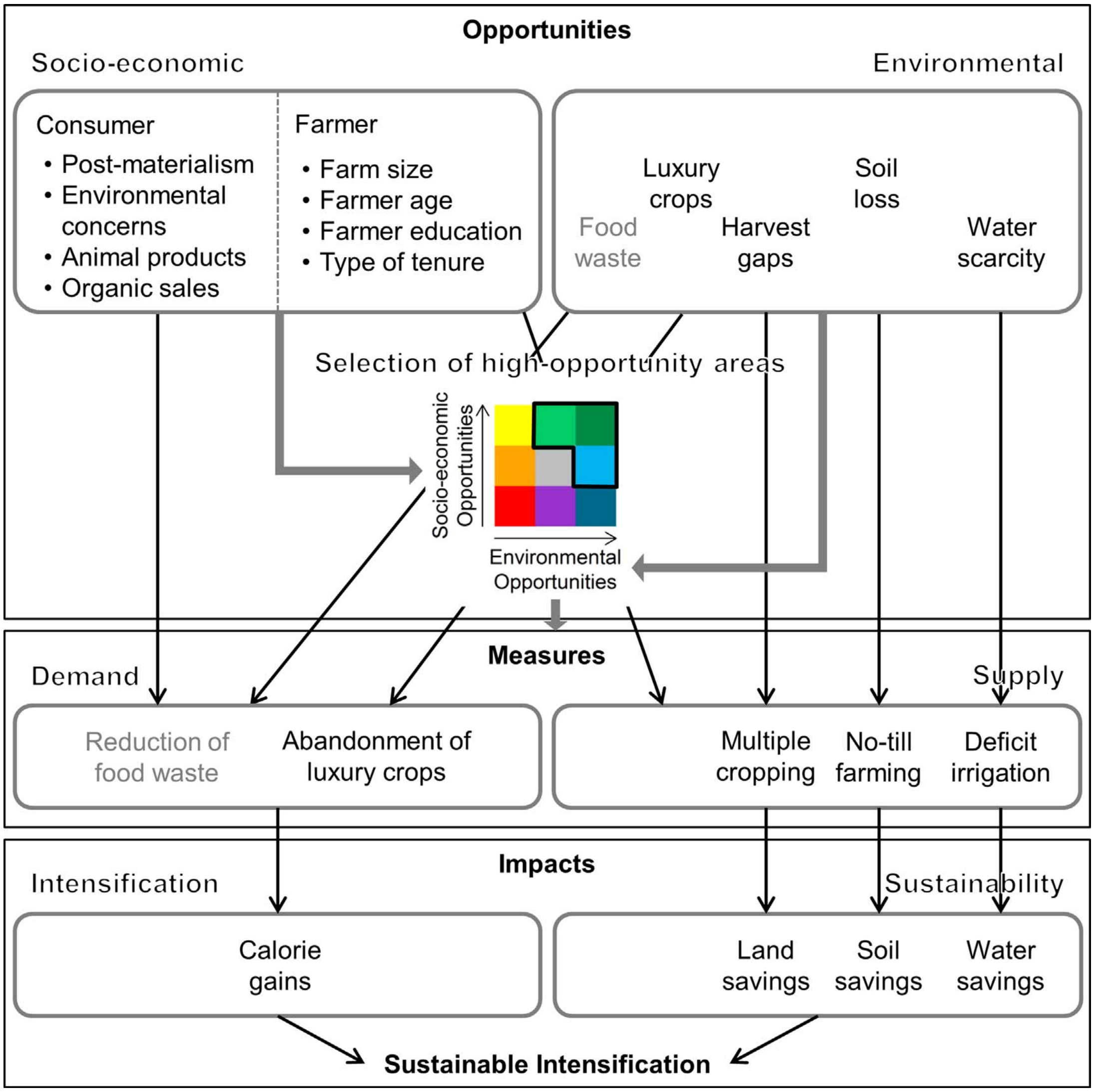

Fig. 1. Conceptual framework for assessing opportunities for sustainable intensification. Both socio-economic and environmental conditions determine the overall opportunities for sustainable intensification. In areas with high opportunities (as highlighted in the colour matrix), it is most feasible to implement measures. These measures have impacts in terms of both food and resource availability, and together they define sustainable intensification. Since the reduction of food waste at the consumption level is independent of the location of agricultural production and the behaviour of farmers, only food waste and consumer opportunities were considered in this case.

at NUTS2 level for farmers and consumers separately. Most socio-economic parameters are given at NUTS2 level, which is a European standardised Nomenclature of Territorial Units for Statistics. Equal weights for the different proxies were assumed, given insufficient evidence for assuming differences in weight. As a sensitivity analysis, we tested the effect on the opportunity categories of using either i) equal weights for farmers and consumers (default) or ii) weighting farmers double (alternative), as they have to implement the changes in the agricultural production.

Table 1
Data sources and characteristics for analysing and mapping socio-economic opportunities for sustainable intensification.

Category	Parameter	Number of classes	Data Source	Year	Resolution	Highest Opportunity
Farmer	Farm size (area)	8	Eurostat	2010	NUTS2	≥100 ha
	Farmer age	5	Eurostat	2007	NUTS2	< 35 years
	Farmer education	3	Eurostat	2010	NUTS2[a]	Full training
	Farm tenure	3	Eurostat	2010	NUTS2	Owner
Consumer	Post-materialism	Continuous	European Values Survey	2008/2009	NUTS2	67% (high)
	Affiliation with environ. NGOs	Continuous	European Values Survey	2008/2009	NUTS2	50% (high)
	Hypothetical donations for the environment	Continuous	European Values Survey	2008/2009	NUTS2	78% (high)
	Organic sales	Continuous	Organic Data Network	2011	Country	7.6% (high)
	Animal product consumption	Continuous	FAOSTAT	2010	Country	644 kcal/cap./d (low)
	Animal product consumption trend[b]	Continuous	FAOSTAT	2002–2011	Country	-27 (kcal/cap./d)/a (low)

[a] Farmer education was downscaled from country to NUTS2 level with data on education of the general population.
[b] Trend derived by linear regression over the years 2002 to 2011.

2.2.1. Cluster analysis

While the main part of the study focusses on current opportunities for sustainable intensification, we performed a cluster analysis to identify countries with similar socio-economic conditions, assuming that such similarities allow for similar approaches to increase future socio-economic opportunities. For grouping the countries based on their current socio-economic opportunities, we first aggregated the data from NUTS2 regions to country averages, weighting by the agricultural area within each NUTS2 region. Affiliations with environmental NGOs and hypothetical donations for the environment were averaged to a single indicator approximating environmental concerns, and animal product consumption and its trend were averaged to an indicator for animal product demand. This data preparation ensured considering an equal number of parameters for farmers and consumers in the cluster analysis.

For clustering, we used Ward's algorithm, which is an agglomerative hierarchical technique. Agglomerative clustering starts with singleton clusters (each data point forms its own cluster) and successively merges the most similar pair of clusters (Berkhin, 2006). According to Ward's method, two clusters are most similar if the within-cluster variance, described by the error sum of squares, is minimal (Ward, 1963). The number of clusters was chosen based on the maximum average silhouette index, which accounts for the compactness and the separation of clusters (Rousseeuw, 1987). Arbelaitz et al. (2013) recommend the index as among the top three cluster validity indices, and possibly the best. We tested forming two to five clusters.

2.3. Environmental opportunities

Environmental opportunities were assessed based on four variables: harvest gaps, soil erosion, water scarcity, and the cultivation of luxury crops. Yield gaps represent an unexploited potential that was not considered in this study, but has extensively been examined (Licker et al., 2010; Neumann et al., 2010; Mueller et al., 2012; Pradhan et al., 2015). These studies show that yield gaps are small in Northern and Western Europe, whereas there is considerable potential to close yield gaps in Southern and Eastern Europe. However, among the multiple options to close yield gaps (Pradhan et al., 2015), a major pathway is irrigation (Mueller et al., 2012), while Southern and Eastern Europe are water scarce, which makes additional irrigation challenging (Pradhan et al., 2015). In contrast, closing harvest gaps by multiple cropping is also relevant for some European countries (Ray and Foley, 2013). It is more water efficient than closing yield gaps (Davis et al., 2016b) and was, therefore, preferred as potential measure.

The input data used to map each of these variables are compiled in Table 2. Each variable was translated to an opportunity indicator that ranges from 0 to 1, and all indicators were finally aggregated using equal weights. To identify the environmental variable with the highest opportunity across the European territory, we calculated the average of each variable. The co-occurrence of two environmental opportunities was based on the spatial overlap of high opportunities ($> = 0.75$) for each pair of variables expressed as a percentage.

2.3.1. Harvest gaps

Harvest gaps exist where multiple crops could be cultivated sequentially on the same land, but this potential is not exploited. The actual cropping frequency was derived by dividing the harvest areas of 42 crops and crop groups by their physical areas at 5′ resolution (You et al., 2014). Although a harvest gap at a specific agricultural field can only represent full crop cycles, the harvest gap of a grid cell covering multiple agricultural fields with different crops can still, on average, be a fraction of a crop cycle. Likewise, the average harvest gap over multiple years can be a fraction. For instance, the minimum is 0.75, which suggests that, in the respective grid cells, the land lies fallow, on average, every 4 years. The potential cropping frequency for annual crops was estimated based on three criteria (Table 3) of which one must be met: 1) the length of the thermal growing period, 2) the degree-days during the frost-free period, and 3) the degree-days during the thermal growing period (Fischer et al., 2012). A potential cropping frequency of 1 was assumed for perennial crops. The classification of crops as annual or perennial is documented in Table A5 (Appendix). The harvest gap (HG) was derived from the difference between potential and actual cropping frequency. Without fallow land, the maximum harvest gap would be 2, and we used this value as upper boundary for scaling the harvest gap to a zero-one range, indicating the opportunities for exploiting them.

Table 2
Data sources and characteristics for mapping environmental opportunities for sustainable intensification.

Parameter	Data source	Year	Resolution
Harvest gaps			
Physical arable area	(You et al., 2014)	2005	5′
Harvested arable area	(You et al., 2014)	2005	5′
Length of thermal growing period	(Fischer et al., 2012)	2000	5′
Temperature sum during the frost-free period	(Fischer et al., 2012)	2000	5′
Temperature sum during the thermal growing period	(Fischer et al., 2012)	2000	5′
Soil erosion			
Soil erosion	(Panagos et al., 2015d)	2010	100 m
Rainfall erosivity (Switzerland)	(Panagos et al., 2015a)	2010	500 m
Rainfall erosivity (Norway)	(Scherer and Pfister, 2015a)	2000	5′
Soil erodibility	(Scherer and Pfister, 2015a)	2000	5′
Digital elevation model	(USGS, 2014)	2010	30″
Land cover	(EEA, 2017)	2006	100 m
Water scarcity			
Irrigation	(Pfister et al., 2011)	2000	5′
Cropland area time series	(Ramankutty and Foley, 1999)	2000–2007	0.5°
River discharge	(Wada et al., 2016)	2001–2010	5′
Dams	(Lehner et al., 2011)	2010	Points
Upstream area	(Wu et al., 2012)	2000	5′
Watersheds	(Masutomi et al., 2009)	2000	Polygons
Luxury crops			
Luxury cropland area	(EC, 2016)	2010	NUTS2
Physical arable area	(You et al., 2014)	2005	5′
Food waste			
Food waste	(Hiç et al., 2016)	2010	Countries
Population	(Doxsey-Whitfield et al., 2015)	2010	30″

Table 3
Criteria for the delineation of multiple cropping zones (Fischer et al., 2012).

Crop cycles	$LGP_{t=5}$[a]	$TS_{t=0}$[b]	$TS\text{-}G_{t=5}$[c]
2	≥240	≥4500	≥4000
3	≥330	≥5700	–

[a] Length of the thermal growing period based on the number of days in the year when average daily temperature exceeds 5 °C
[b] Temperature sum when average daily temperature exceeds 0 °C
[c] Temperature sum during the thermal growing period when average daily temperature exceeds 5 °C

2.3.2. Soil erosion

Soil loss rates in 2010 were obtained from the European Soil Data Centre for the EU at a resolution of 100 m (Panagos et al., 2015d). They estimated soil loss with the revised universal soil loss equation (RUSLE). In order to match the resolution of other gridded datasets used in our analysis, we aggregated raster cells by averaging the smaller cells

(100 m) contained in the new larger cell (5′). Values for Switzerland and Norway were calculated using a similar methodology. Rainfall erosivity (R) for Switzerland was taken from Panagos et al. (2015a). R for Norway and soil erodibility for both countries were calculated as by Scherer and Pfister (2015a), but R was bias-corrected by the ratio of the medians of the overlapping areas and limited to a maximum of 6000 MJ mm ha^{-1} h^{-1} yr^{-1}. The slope length factor was set to 2 (Summer et al., 1996; Knijff van der et al., 2000; Cerdan et al., 2010) and the slope steepness factor was derived from a digital elevation model (USGS, 2014) following Nearing (1997). The cover management factor (C) was calculated by reclassifying Corine land cover classes (EEA, 2017) using the mid-range value of corresponding C ranges (Panagos et al., 2015b), and subsequently aggregating the grid cells to 5′ by averaging. The support practice factor (P) was estimated by reclassifying six slope classes (following Panagos et al. (2015c) completed with 0–9%) derived from the digital elevation model (USGS, 2014) using the EU's average P (Panagos et al., 2015c) for these classes.

Erosion rates (E) exceeding 5 t ha^{-1} yr^{-1} are considered as unsustainable (Panagos et al., 2015d) and were assigned the value ($O_{erosion}$) 1 for indicating its high opportunity. In contrast, rates below 0.5 t ha^{-1} yr^{-1} are considered negligible and assigned a value of 0 because soil formation is likely to be as fast or even faster than erosion. Soil formation was derived from soil thickness increase (Sauer et al., 2015) and soil bulk density (Tranter et al., 2007; Sequeira et al., 2014). Rates between the two boundary values were linearly scaled to the range 0 to 1.

2.3.3. Water scarcity

Agriculture, as the largest global water consumer, both increases water scarcity and is affected by water scarcity. In this study, we described the severity of water scarcity by a monthly water scarcity index (WSI_{mon}) ranging from 0.01 (low water scarcity) to 1 (high water scarcity) (Pfister and Bayer, 2014b):

$$WSI_{mon} = \frac{1}{1 + e^{-c \cdot CTA_{mon} \cdot s_{year}^*} \cdot \left(\frac{1}{0.01} - 1\right)}$$

c is a calibration coefficient that depends on the temporal resolution, water source and type of water use considered. Here, we used 26.6 as calibration coefficient for monthly consumption of total water (surface and groundwater) (Scherer et al., 2015b).

CTA_{mon} is the monthly water consumption-to-availability ratio. Only irrigation was considered for water consumption, which covers almost 90% of all water consumption at the global level (Shiklomanov and Rodda, 2004), and 64% in the EU28 (Vanham and Bidoglio, 2013). In addition, it is most relevant for improving water-related agricultural sustainability. It was obtained from Pfister et al. (2011) at a 5′ resolution and extrapolated from the year 2000 to the years 2001–2010 relative to the changes in cropland area until 2007 (updated version of Ramankutty and Foley, 1999) and from 2008 to 2010 by assuming a constant change equal to the average change in the previous years. River discharge was assumed to represent total water availability, although some add river discharge and groundwater recharge to estimate total water availability. River discharge includes baseflow which comes from groundwater. Therefore, groundwater recharge is partly accounted for, while the alternative approach would lead to partial double counting. The data was provided by Wada et al. (2016) at a 5′ resolution. For both water consumption and availability, monthly averages were calculated for the decade 2001–2010.

s_{year}^* is either the geometric standard deviation of annual water availability (for non-regulated river flow) or the square root thereof (for regulated river flow). We used river discharge to calculate s_{year}^*. As in Scherer and Pfister (2016a), rivers were considered as strongly regulated when the upstream area up to the nearest upstream dam (Lehner et al., 2011) covered less than half the total upstream area (Wu et al., 2012) within the watershed (Masutomi et al., 2009).

The value indicating the opportunities (O_{water}) was set equal to the annual average of the monthly WSIs weighted by monthly water consumption (WC_{mon}):

$$O_{water} = WSI = \frac{\sum_{n=1}^{12} WSI_{mon,i} \cdot WC_{mon,i}}{\sum_{n=1}^{12} WC_{mon,i}}$$

2.3.4. Cultivation of luxury crops

Feeding human-edible food crops to livestock drains the food supply to humans because animals convert these crops to human-edible food, such as meat and dairy products, at a low efficiency (Foley et al., 2011). In European regions, 51–86% of the produced crop calories are fed to livestock, which only return one third to one fifth of these crop calories as animal calories (Pradhan et al., 2013). Livestock only adds to human food supply if the animals are raised on land unsuitable for crop production and feed is supplemented with by-products from crop cultivation and food processing, without wasting human-edible crops to feed livestock (van Kernebeek et al., 2016). Also alcoholic drinks contribute little to food security and dietary quality given their low nutrient contents (USDA, 2016). Still, crop cultivation for alcohol production causes the same environmental impacts as crop production for other purposes (Gazulla et al., 2010). In addition, agricultural land is used for non-food applications such as biofuels, tobacco, and ornamental crops, each of which is associated with environmental degradation (biofuels: Pfister and Scherer, 2015, tobacco: Lecours et al., 2012, ornamental crops: Wandl and Haberl, 2017). All these crops and crop-derived products can be considered as luxury crops and using the land occupied by these crops differently could either increase food availability or decrease land occupation and other environmental impacts.

The agricultural area used to grow luxury crops within a NUTS2 region from Eurostat (EC, 2016) was disaggregated to 5′ grid cells by relating it to specific crop categories from the gridded crop data (You et al., 2014) (Table 4). Biofuels were represented by rapeseed, as it is the dominant feedstock for biofuels in Europe (Duren et al., 2015), while animal fodder was represented by maize because it is one of the major fodder crops in Europe, especially for cattle (Herrero et al., 2013), and its dominant use in developed countries is for animal feed (Shiferaw et al., 2011). Alcoholic drinks were represented by vineyards only. Crop production for beer, cider, and spirits cannot be separated from production for other purposes, while grape production in Europe is mostly for the purpose of wine production (27 million tonnes of grapes were produced in Europe in 2014 (FAO, 2016); assuming a mass fraction of 0.7 for converting grapes to wine (Scherer and Pfister, 2016b), 19 million tonnes of wine could potentially be produced from that; this compares to an actual wine production volume in Europe in 2014 of 18 million tonnes (FAO, 2016)).

The gridded crop areas were multiplied with the ratio of the Eurostat values to the mean of the gridded crop areas within the same NUTS2 region. In NUTS2 regions without information in Eurostat, the median ratio over all available NUTS2 regions was used. In contrast, if no cultivation was assumed in the gridded crop data, but production is registered in Eurostat, the cultivated area from Eurostat was equally

Table 4
Selection of luxury crops and the assignment between categories in Eurostat and the gridded dataset.

Luxury crop category	Gridded crop category	Major stakeholder
Animal fodder	Maize	Consumer
Wine	Temperate fruits	Consumer
Biofuel	Rapeseed	Government
Tobacco	Tobacco	Consumer
Ornamental crops	Rest of crops[a]	Consumer

[a] Rest of crops is a crop group from the gridded crop data that includes all remaining crops not yet covered by the other 41 crops and crop groups.

distributed among all cells within the NUTS2 region which are used for agriculture following the gridded crop areas (You et al., 2014). Next, the separate maps of luxury crop areas were added up. Where the disaggregation and sum of all considered luxury crops led to agricultural areas (AA) larger than 8498 ha within a grid cell (the maximum in Europe for the considered crop categories), the variation of grid cells within a NUTS2 region was reduced by an attenuation factor (AF) so that the maximum area of total luxury crops in the grid cell was limited to 8498 ha:

$$AF\,(region) = \frac{\mathrm{AA}_{\max}(region) - \mathrm{AA}_{mean}(region)}{8498 - \mathrm{AA}_{mean}(region)}$$

$$\mathrm{AA}^{*}(cell) = \frac{\mathrm{AA}(cell) - \mathrm{AA}_{mean}(region)}{AF\,(region)} + \mathrm{AA}_{mean}(region)$$

The agricultural area used to grow luxury crops within a grid cell was divided by the maximum agricultural area of all grid cells within Europe (8498 ha) to normalize the indicator for the opportunities from zero to one.

2.3.5. Food waste

Globally, food losses are estimated to be between 10 and 50% (Parfitt et al., 2010). Reducing these losses to a realistic level was shown to reduce the environmental impacts of food production by about 12% (Hoolohan et al., 2013; Kummu et al., 2012). In affluent countries like in Europe, most food is wasted by consumers (Parfitt et al., 2010). Therefore, we considered food waste as a demand-side measure and calculated it as the product of the per-capita food waste (Hiç et al., 2016) and the population count (Doxsey-Whitfield et al., 2015). The total food waste at a location was subsequently divided by the maximum value to limit the value indicating the opportunity to 1.

2.4. Sustainable intensification measures

2.4.1. Multiple cropping

Multiple cropping enables to produce more food on the same area of land, which results either in land sparing elsewhere or in higher food production. Although multiple cropping might increase the environmental pressure locally, we assume that the benefits from land sparing outweigh that. As a sustainable intensification measure, we completely fill the harvest gap with additional crop cycles, assuming the average yield within the grid cell as the yield of the additional crops in sole cropping. With an actual cropping frequency of 1 and a harvest gap of 1, closing the harvest gap would double the cropping frequency and, thus, save 50% of the land if yields would not be reduced. However, a crop is likely to achieve lower yields in multiple cropping compared to sole cropping, because sowing dates might be suboptimal and growth durations shorter. Land savings (LS, ha) are, then, calculated as:

$$\mathrm{LS} = \mathrm{AA}\cdot\left(1 - \frac{\mathrm{CF}}{\mathrm{HG}\cdot(1{-}\mathrm{YL}){+}\mathrm{CF}}\right)$$

AA is the agricultural area in ha, HG is the harvest gap, CF is the actual cropping frequency, and YL is the yield loss. We assumed that the yield of the existing major crop remains unaffected, while the second (and possibly third) crop has a yield loss of 34% resulting from the mutual effect of shifting the sowing date by 30 days (yield loss of 22%) and reducing the growing period by 30 days (yield loss of 15%). These yield losses were estimated based on average yield losses due to shifts of the sowing date scaled to 30 days (Caliskan et al., 2008; Coventry et al., 2011; Liu et al., 2013) and due to a reduction of the growing period by 20 to 40 days (Caliskan et al., 2008).

2.4.2. No-till farming

The most effective measure to prevent soil loss under continuation of arable farming is no-till farming, given the large range of the tillage factor (Panagos et al., 2015b). The factor ranges from 1 for conventional tillage to 0.25 for no-till farming, meaning that the site-specific potential to reduce erosion (E) is up to 75%. Conventional tillage is common practice in Europe so that the potential for implementing no-till farming is also high in practice. Tillage factors ($C_{tillage}$) from the European Soil Data Centre (Panagos et al., 2015b) are used and a decrease in the tillage factor directly translates to the same decrease in soil loss or to soil saving (SS, in t).

$$\mathrm{SS} = \mathrm{E}\cdot(\mathrm{C_{tillage}} - 0.25)/\mathrm{C_{tillage}}\cdot\mathrm{AA}$$

Yield response to no-till farming greatly varies, especially depending on the crop category and the aridity index. The effects are lower in temperate regions than in the tropics, and we assumed generic yield losses of 3.4% for Europe, which is the average value for temperate regions (Pittelkow et al., 2015). The food loss (FL, million people fed) is then:

$$\mathrm{FL} = \mathrm{YL}\cdot\mathrm{AP}\cdot\mathrm{CC/ER}$$

AP is the agricultural production in tonnes (You et al., 2014). We excluded fibres and stimulants, as they do not contribute to food security. CC is the caloric content of the respective crops (FAOSTAT).

ER are the average daily human energy requirements. We assume 2523 kcal/(day·capita), which are the population-weighted (Doxsey-Whitfield et al., 2015) average requirements (Hiç et al., 2016) of the European countries included in our study.

2.4.3. Deficit irrigation

Deficit irrigation is a strategy to optimize water productivity – the crop yield per volume of water consumed – in order to save irrigation water at the expense of no or only marginal yield losses (Costa et al., 2007). Wriedt et al. (2009) simulated different irrigation scenarios in Europe (Switzerland and the EU without Croatia), including full irrigation (to achieve the maximum yield), rain-fed agriculture (no irrigation), and three deficit irrigation schemes. They used the crop growth model EPIC at a 10 km resolution for 34 crops and crop groups and provide summary results of irrigation reductions (IR) and yield losses for five crops regions (Table 3 in Wriedt et al., 2009, Table A6 and Fig. A1 in the Appendix). We assume that full irrigation is the current practice, given the lack of information for a more accurate assumption, and choose an irrigation scenario with a maximum of 10% yield loss to limit the loss of food calories (Table 5). For some regions, that required interpolation between two of Wriedt et al.'s (2009) irrigation scenarios. Water savings (WS, in million m^3 H_2O_e) are calculated as:

$$\mathrm{WS} = \mathrm{WC}\cdot\mathrm{WSI}\cdot\mathrm{IR}$$

Food losses are calculated as in Section 2.4.2.

2.4.4. Abandonment of luxury crop cultivation

In contrast to the aforementioned supply-side measures, the abandonment of luxury crop cultivation is a demand-side measure. It involves consumers reducing their consumption of meat, alcohol, and cigarettes and their purchase of ornamental plants, and governments to abandon biofuel targets. Apart from limiting land requirements in Europe, it helps to avoid displacing impacts to outside of Europe. The land used for the cultivation of luxury crops can either be spared from

Table 5
Deficit irrigation scenarios for different European regions derived from Wriedt et al. (2009).

Crop region	Yield loss	Irrigation reduction
Mediterranean	10%	34%
Alpine	10%	89%
Continental	10%	77%
Atlantic	10%	90%
Boreal	2%	100%

agriculture or be used for the cultivation of nutritious crops that contribute to food security. Here, we assumed that the land is used to grow the staple food crop (barley, maize, potato, rice, wheat, other cereal) with the highest harvested production within each NUTS2 region (EC, 2016). The availability of calories from macronutrients are the primary prerequisite for food security (Barrett, 2010), and maize, rice, and wheat alone supply humans with about half of the dietary energy (FAO, 2014). This highlights the importance of cereals for food security. Maize is only considered a luxury crop if it is fed to animals. Besides cereals, potatoes are an important food source and especially European per-capita consumption is high (Camire et al., 2009). Still, the choice of staple foods is a simplification and might lead to an overestimation of the benefits, as also a nutritional balance is important for food security (Barrett, 2010) to avoid hidden hunger (Ruel-Bergeron et al., 2015). Since vineyards are also commonly found in mountainous areas (Stanchi et al., 2013), which are unsuitable for the production of staple food, grapes were not replaced in areas with slopes ≥ 9% (EPA, 2016), but they were assumed to be consumed directly, without processing to wine.

The food gain in terms of calories (FG, million people fed) can be derived by:

$$FG = AA \cdot AY \cdot CC/ER$$

AY is the agricultural yield ($t\,ha^{-1}$). We assumed the same cereal yield as the crop's average in the respective NUTS2 region and converted the additional food production to calories based on caloric contents (CC, kcal/t) obtained from the food supply information on crops primary equivalents in the European Union from FAOSTAT (FAO, 2016).

2.4.5. Reduction of food waste

For reducing food waste, we assumed that consumers can reduce the food waste share, as the ratio of the per-capita food waste to the human energy requirements (Hiç et al., 2016), to 4%. This is the minimum share within Europe by Cyprus. In contrast, Belgium reaches the maximum, in Europe and globally, with 51%.

3. Results

3.1. Socio-economic and environmental opportunities

Country averages of socio-economic opportunities (Fig. A2-4 in the Appendix) were divided into three clusters (silhouette index = 0.26, Fig. 2, Fig. A5 in the Appendix). The cluster with the highest socio-economic opportunities on average is best represented by Austria (Cluster 3). They stick out with a high share of organic product sales, have high environmental concerns and a high share of post-materialists. All three factors are related to consumers. The cluster with the second highest socio-economic opportunities is best represented by France (Cluster 2). In contrast to the first group, these countries rather have high opportunities related to farmers. They have the most educated farmers, who are also among the younger farmers with the largest farms. The last cluster is best represented by Norway (Cluster 1). These countries have the most farmers who own the farm they are working on, but the farms are small and farmers are the oldest and least educated.

The highest environmental opportunities (Fig. A6-8 in the Appendix) are associated with harvest gaps, followed by soil erosion and water scarcity, while the lowest opportunities exist in terms of the cultivation of luxury crops and food waste (Fig. 3, Table 6). Harvest gaps often co-occur with water scarcity, which indicates that agricultural production in those regions is constrained by water rather than temperature. Harvest gaps are especially high in the UK, Ireland, France, and Spain. France and Spain are also water scarce, as are Italy, Greece, Romania, and even some northern regions like Denmark. Soil erosion is high in mountainous regions like the Alps (Switzerland and Austria), the Apennines (Italy), the Carpathians (Romania), and the Scandes (Norway). Luxury crops are especially cultivated in Germany with the large majority being animal fodder. Food waste in concentrated in big cities such as Athens, London, and Paris.

The highest opportunities for sustainable intensification, considering both the society and the environment, are found in France, Italy, and Denmark (dark green in Fig. 4). Although there are large environmental potentials in Portugal, Greece, and Romania, they are constrained by the socio-economic conditions in these countries (dark blue in Fig. 4). In contrast, Sweden and Estonia have suitable socio-economic settings, but there is less need for resolving environmental problems (yellow in Fig. 4). In the following, we will consider areas with high opportunities with regards to both the environment and socio-economic characteristics, and areas with high opportunities with regards to one and moderate opportunities with regards to the other aspect as high opportunity areas (light blue, light green and dark green in Fig. 4), for which we quantify the impacts of sustainable intensification measures. Together, they represent about 34% of the arable area in the European countries under investigation. The estimate ranges from 33 to 39% in the sensitivity analysis (Fig. A9-13 in the Appendix). It is slightly lower when weighing farmers double than consumers and higher when using tertiles instead of quartiles for categorizing the opportunities.

3.2. Sustainable intensification measures

In high opportunity areas, the implementation of sustainable intensification measures leads to both resource savings and additional food production (Table 7, Table A7 in the Appendix). For multiple cropping, we assume that land is spared, while luxury crops are replaced by staple food crops and food waste results in additional food instead of less production. In doing so, we prevent major changes in employment that would result from either additional land availability or land abandonment. Although there are trade-offs for no-till farming and deficit irrigation which cause slight yield losses, the five measures together result in benefits of both intensification and sustainability.

Land use can almost be halved in the high opportunity areas, while water scarcity and soil loss can be reduced by about 60 and 70%. In addition, almost 40% more calories could be produced by reducing food waste and replacing luxury crops such as animal fodder by staple food crops directly consumed by humans. Biofuels, as luxury crops demanded by governments, play a smaller role than those demanded by consumers.

4. Discussion

4.1. Implications and comparison with previous studies

Opportunities for sustainable intensification vary spatially across Europe. Both socio-economic and environmental conditions limit its potential. Among the farmer characteristics suggesting a higher willingness to adopt sustainable intensification practices, the age provides the lowest opportunities (Fig. 2). European farmers are rather old, and the ageing of rural populations (Burholt and Dobbs, 2012) and farmers in Europe (Zagata and Sutherland, 2015) indicate that the age structure will be less favourable for the adoption of sustainable and innovative practices in the future. Where there are young farmers, they are often more educated than the older farmers (Pearson correlation coefficient between opportunity indicators at NUTS2 level for age and education = 0.55), in line with the general massification of education in Europe and the world (Altbach, 2015). The higher education additionally supports pro-environmental behaviour (Meyer, 2015). However, rather than a 'young farmer problem', Zagata and Sutherland (2015) postulate a 'small-scale farming problem'. Although, the farm size seems to provide the highest opportunities with regards to farmers in our study (Fig. 2), the negative correlation with farm tenure (-0.52)

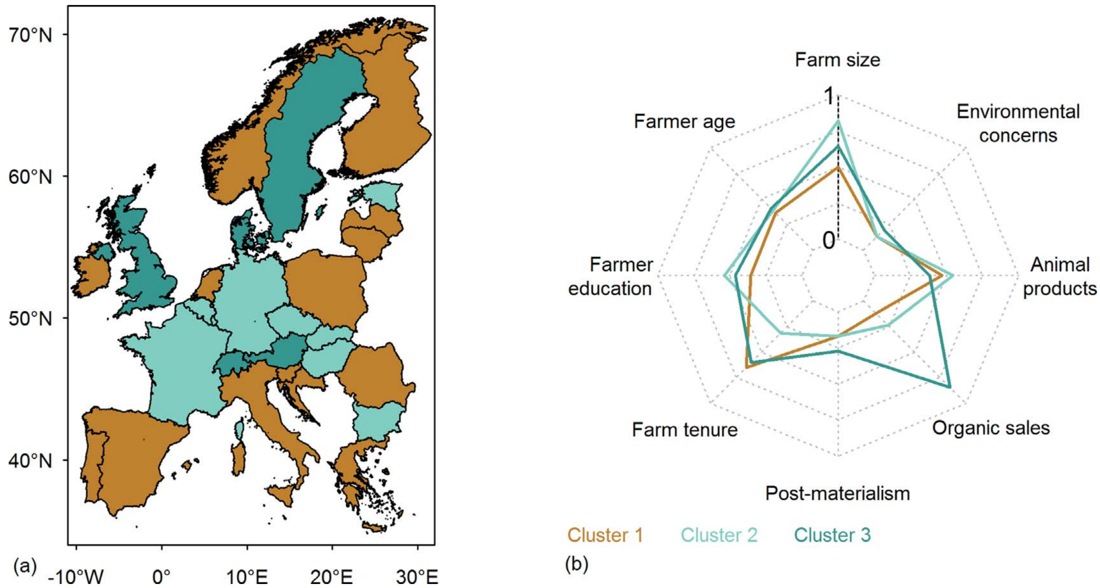

Fig. 2. Clusters of countries based on their socio-economic opportunities for sustainable intensification. The clusters are derived from Ward's algorithm, an agglomerative hierarchical technique. (a) The map shows three clusters of countries. Countries from the same cluster are coloured alike. (b) The radar chart shows the average socio-economic opportunities of country clusters. The line colours refer to the country colours in sub-figure a.

suggests a lack of large-scale farmers who own the farm. Overall, farmer opportunities are lowest in Mediterranean countries, which is consistent with the higher risk of farmland abandonment in the same region (Terres et al., 2015).

With regards to consumers, the two opposing peaks for organic and animal products are striking (Fig. 2). Two phenomena might explain that finding. First, the consumption of both types of products might increase with wealth. Animal product consumption is higher in richer, developed countries than in less wealthy, developing countries (Kearney, 2010), while the high price premiums for organic products are a major barrier for their consumption (Aertsens et al., 2009). So, price and income might determine their consumption rather than pro-environmental attitudes. In addition, a market for organic products must exist to enable their purchase. Second, contribution ethic or moral licensing might play a role: people might think that they have already contributed a fair share to environmental protection by either action, their moral self-image is heightened and, as such, they justify refraining from other pro-environmental behaviours (Thøgersen and Crompton, 2009; Truelove et al., 2014). Altogether, opportunities are lower with regards to consumers than farmers; however, consumer characteristics might also be less decisive for the adoption of sustainable intensification than farmer characteristics due to the spatial disconnection

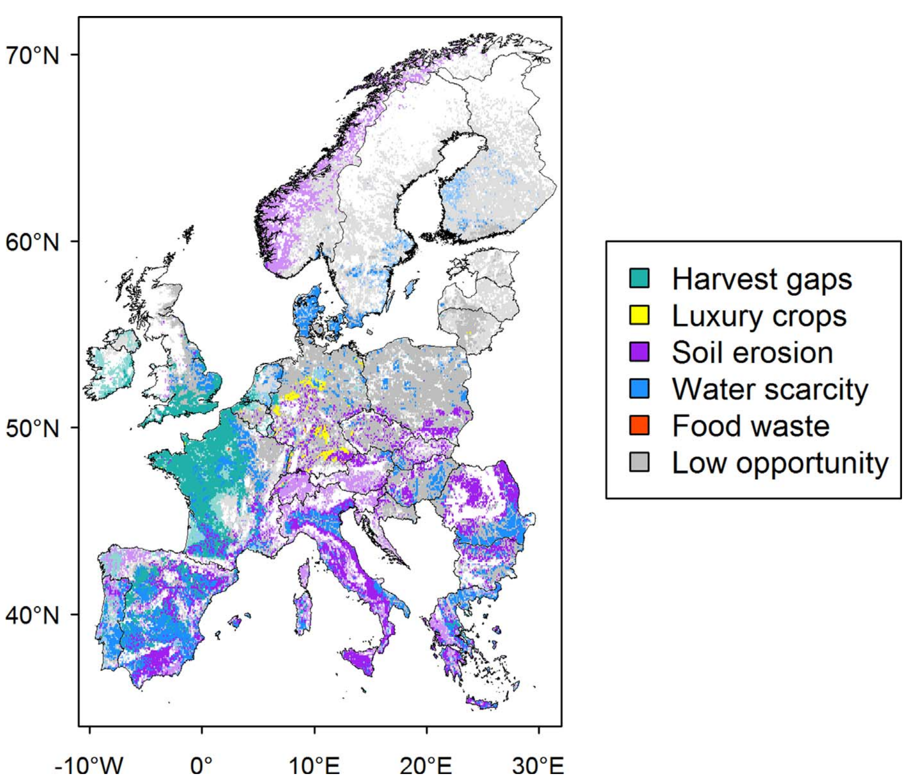

Fig. 3. Environmental variable determining the highest opportunity for sustainable intensification. Environmental opportunities are based on four environmental variables. Where opportunities are high, this map highlights which variable is most decisive. Less opaque colours indicate arable areas of < 1000 ha. White indicates no crop production.

Table 6
Average opportunities for different environmental variables over Europe and percentage overlap of these among areas with high opportunities (≥ 0.75). The overlap is expressed as a percentage of the row variable.

Opportunity	Harvest gap	Soil erosion	Water scarcity	Luxury crops	Food waste
Average	0.36	0.29	0.21	0.06	0.004
Percentage overlap of opportunity indicators ≥ 0.75					
Harvest gap	–	8	31	0	0
Soil erosion	4	–	18	0	0
Water scarcity	22	22	–	0	0
Luxury crops	8	1	14	–	0
Food waste	0	0	0	0	–

between consumption and production (Scherer and Pfister, 2016b).

Harvest gaps have previously been estimated in a global study at country scale. As in this study, Ray and Foley (2013) only used a thermal criterion to determine the potential for multiple cropping. They also identified harvest gaps in Ireland and Southern Sweden; however, their harvest gap in France is much smaller than the one identified in this study. Almost one third of the harvest gaps coincide with water scarcity (Table 6). Therefore, closing the harvest gap might not be attainable. The importance of considering water resources in conjunction with harvest gaps is also demonstrated by a Chinese study where the harvest gap differs by almost a factor of 3 depending on the water allocation scenario (Yu et al., 2017).

Previous estimates of water scarcity are consistent with this study in identifying high scarcity in the Mediterranean, whereas the different models agree less for other regions, such as Denmark (Pfister and Bayer, 2014a; Luo et al., 2015; Scherer and Pfister, 2016a). Differences might be explained by either relating water scarcity to water consumption, as in this study, or to water withdrawal and by different sources for the input data. For erosion, the dataset used in this study predicts higher erosion rates (Panagos et al., 2015d) than previously estimated based on a spatial extrapolation of plot data (Cerdan et al., 2010). Higher estimates are especially found in the Alpine and Mediterranean region, which are characterized by high rainfall intensities, a variable neglected in the previous approach.

Numerous studies have shown the effects of different diets on the environment. They have especially demonstrated that a diet with less animal products embodies less land (Alexander et al., 2016; Kastner et al., 2012; Springer and Duchin, 2014) and is beneficial in other environmental aspects (Marlow et al., 2009; Springer and Duchin, 2014). In our study, 85% of cropland under luxury crops is used for fodder production. Few studies have considered other luxury crops, such as alcoholic beverages and stimulants. In our study, vineyards contribute 13% to luxury cropland. Kastner et al. (2012) found that stimulants contribute 2–7% to total cropland requirements in Europe, while alcoholic beverages contribute 3–4% − shares that are only exceeded by animal feed, cereals, and vegetable oils. These other luxury crops can have significant environmental impacts without contributing to food security. For example, regarding water scarcity, Scherer and Pfister (2016b) identified grapes as among the ten highest water scarcity footprints for Swiss consumption. However, the authors note a possible overestimation because wine grape irrigation is regulated in Europe. Although animal products are most responsible for differences in environmental impacts per diet, the impact of production of other luxury crops on resource use should also be investigated more thoroughly.

The socio-economic and environmental opportunities were mapped by means of an opportunity matrix. Areas with high opportunities in both aspects (dark green in Fig. 4) are most promising and should be given priority for the adoption of sustainable intensification. In areas with low environmental opportunities but high socio-economic opportunities (yellow in Fig. 4), such as Sweden and Estonia, there might be other environmental opportunities than those considered in this study, such as eutrophication in Sweden (Engström et al., 2008) or yield gaps in Estonia (Mueller et al., 2012). The favourable socio-economic conditions indicate that these areas can be promising for implementing more sustainable practices. In contrast, in areas with low socio-economic opportunities but high environmental opportunities (dark blue in Fig. 4), such as Portugal or Romania, institutions and networks should be strengthened to facilitate the adoption of new agricultural practices. Although the clustering is only weak with a silhouette index of 0.26

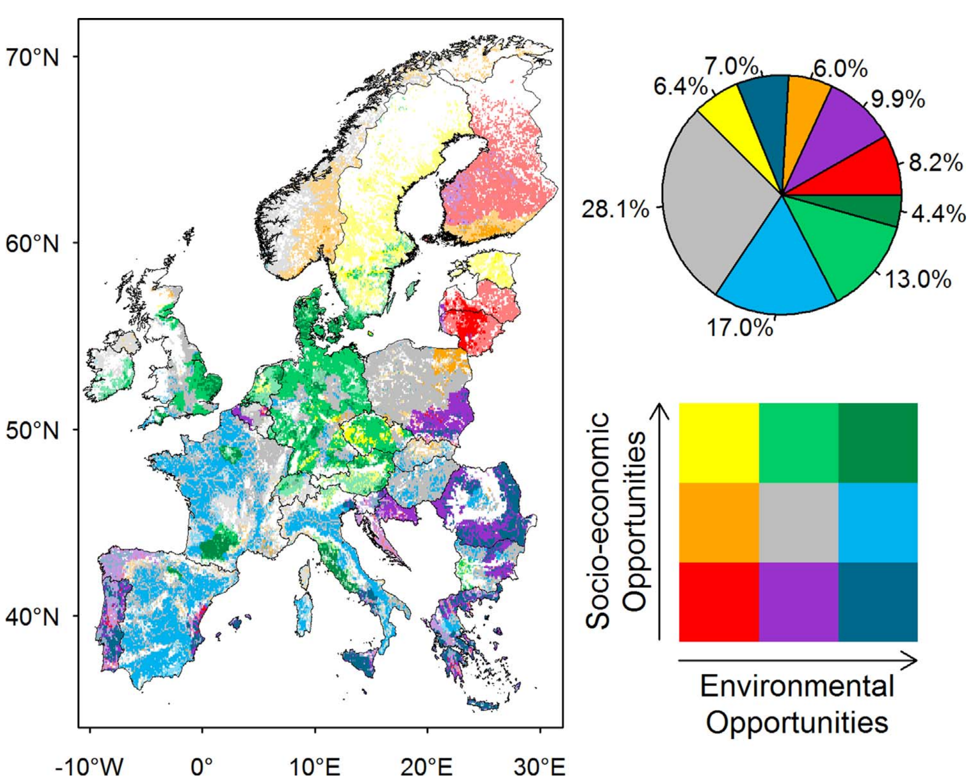

Fig. 4. Opportunity areas for sustainable intensification in Europe. Opportunities depend on socio-economic and environmental conditions (food waste is excluded here). Their synergies and trade-offs are depicted with a colour matrix. Less opaque colours indicate grid cells with < 1000 ha (~10%) arable area. White indicates no crop production. The pie chart displays the share of each opportunity category. The GIS data shown in this figure are available at http://vital.environmentalgeography.nl/.

Table 7
Environmental benefits and changes in food availability after implementing the sustainable intensification measures. Apart from the last row, the values above the dashed line represent changes for only implementing a single measure. The total food gains (last row) are less than the sum of food changes of the individual measures above, as the yield losses from no-till farming and deficit irrigation are multiplicative and also apply to food replacing luxury crops.

Measure	Environment	ΔEnvironment (fraction)	Food	ΔFood (fraction)
Multiple cropping	16 million ha land	0.41		
No-till farming	11 million t soil	0.71	-19 million people	−0.03
Deficit irrigation	17 billion m^3 H_2O_e	0.60	-61 million people	−0.10
No luxury crops (government)			5 million people	0.01
No luxury crops (consumer)			348 million people	0.56
Less food waste			0.3 million people	0.0005
Total			229 million people	0.37

(Kaufman and Rousseeuw, 2005), Portugal and Romania, falling within the same cluster of socio-economic characteristics, might be steered towards sustainable intensification with similar interventions.

4.2. Limitations of the approach

Mapping of opportunities for sustainable intensification would ideally involve intensification and all three sustainability dimensions. However, there are conceptual limitations: the complexity of the topic renders it unfeasible to quantitatively assess all aspects, and there is a lack of knowledge on the strengths of the different influencing factors. To limit the complexity, we focus on opportunities related to resource use and on one measure per environmental opportunity. We selected the most vital resources and the measure with the highest potential gain or easiest implementation. Besides the environmental opportunities, we also assess the social uptake by farmers and consumers.

These simplifications imply that we disregard the loss of ecosystem services and biodiversity. Including areas with a need for restoration of biodiversity or ecosystem services might result in identification of different areas with opportunities for sustainable intensification.

Also, the simplifications imply that socio-economic impacts are mostly neglected. Food security was addressed in terms of calories, only providing information on food availability. The effect of replacing luxury crops on food security might be overestimated because no balanced nutrition is ensured. In addition, economic impacts of farming practices are poorly documented so far (Garibaldi et al., 2017; Rasmussen et al., 2017), but the importance of including such considerations is highlighted by the fact that agriculture is a large employer in several European countries (World Bank, 2016). Accounting for economic impacts might lower the potential of sustainable intensification, but, to limit such impacts, we aimed to keep the amount of labour stable upon calculating the impacts of sustainable intensification measures.

Regarding the measures, selecting one measure per environmental opportunity does not embrace the multitude of possible measures towards sustainable intensification (Weltin et al., submitted). Freshwater scarcity, for instance, could alternatively be alleviated by technological progress like increased irrigation efficiency and seawater desalination, and by so called soft-path solutions like dietary changes and regional optimization (Scherer and Pfister, 2016a). Erosion risk could also be decreased through, among others, contour farming and stone walls (Panagos et al., 2015c). However, these have a lower potential than no-till farming and would, thus, lead to smaller improvements. Not limiting the substitution of luxury crops to a few staple food crops would also allow to increase crop diversity, which enhances the agro-ecosystem resilience (Matsushita et al., 2016).

Besides conceptual limitations, mapping of opportunities for sustainable intensification is constrained by data availability. For example, the willingness of farmers to adopt sustainable intensification is also influenced by social capital and networks, the quality of extension services, and institutional support (Kassie et al., 2015). Information is crucial to the adoption, and peer-learning seems to be the primary source of new knowledge (Saint Ville et al., 2016; Schneider et al., 2009). However, Schut et al. (2016) and Bojnec and Latruffe (2007) identify economic and institutional factors, such as access to credits and markets, as among the most significant constraints for sustainable intensification. Data on these additional socio-economic factors were, however, not available at the European scale. Although subsidies can motivate farmers to adopt more sustainable agricultural practices (Prager and Posthumus, 2010), they might only lead to temporary adoption if not accompanied by knowledge transfer and better access to markets (Läpple, 2010).

Consumer behaviours such as buying organic food and donating money to environmental NGOs do not imply missing pro-environmental attitudes. It might as well be related to missing financial means or unawareness of the environmental impacts. Still, the ability to behave in an environmentally friendly way is necessary to create an opportunity.

Also due to data availability, not all luxury crops could be considered in this study. Europeans are the largest alcohol consumers worldwide, and most notably consume beer (Popova et al., 2007). Germany is a major beer brewer, but also every other EU country produces beer (FAO, 2016). Other alcoholic drinks disregarded in this study, but consumed in Europe include brandies, spirits, and vodka (Popova et al., 2007). Still, wine is among the most consumed alcohols in Europe, especially in the Mediterranean (Popova et al., 2007), and together with ornamental crops, tobacco, biofuels, and animal fodder, we cover a considerable share of luxury crops produced in Europe.

Finally, rebound effects might apply, which means that productivity gains from intensification might lead to agricultural expansion rather than land savings (Ceddia et al., 2013), especially when the intensification is market-driven (Byerlee et al., 2014). This is, however, difficult to quantify. We did also not consider the alternative use of the saved resources. In the past, for example, abandoned farmland was often converted to forests, which can also damage the environment when managed intensively (Levers et al., 2014). Where consumers save money, for example when switching from a conventional to a vegetarian diet, this might also lead to rebound effects: The people might respend the savings on more environmentally intensive goods, which lowers the effect of the pro-environmental behaviour (Grabs, 2015). Together with the contribution ethic mentioned above, this highlights the difficulty in predicting consumer behaviour in favour of sustainable intensification by pro-environmental proxy behaviours as done in this study.

4.3. Socio-economic and environmental impacts of implementing sustainable intensification measures

The sustainable intensification measures included in this study influence more sustainability components than assessed. First, the measures influence farm profitability (the difference between income and costs (Garibaldi et al., 2017)) and with that the economic sustainability of implementing the measures. Higher crop yields as a result of intensification contribute to higher income, but good market access must be ensured so that the additional produce can also be sold. The switch from luxury crops to staple crops also most likely affects income. For example, tobacco has a 4–8 times higher economic yield than the cereals rice, soya beans, and maize (Leppan et al., 2014). The more efficient use of land, soil, and water under the measures included here can contribute to reducing costs. For example, saving land by multiple cropping reduces investments in or rent payments for land. No-till farming reduces production costs by requiring less machinery and fuel (Soane et al., 2012). The economic viability of deficit irrigation depends on commodity prices, irrigation systems, and farm size (Rodrigues et al., 2013).

The environmental measures also interact with the environment in more ways than analysed here. For example, no-till farming, does not only reduce soil erosion but also enhances carbon sequestration (Liu et al., 2014), reduces freshwater eutrophication by phosphorus emissions (Scherer and Pfister, 2015a), and increases water and fertilizer use efficiencies (Triplett and Dick, 2008), while it also changes soil biodiversity (Capelle et al., 2012), and increases the occurrence of weeds and pests (Triplett and Dick, 2008). Also, we have not simulated mutual effects of multiple measures that might lower or increase overall changes in yields and resource availability. As an example, replacing luxury crops with staple food crops changes the irrigation requirements and the food waste share.

Although we considered the socio-economic opportunities for implementing sustainable intensification measures, there might be additional challenges to implementing these measures, or innovative practices in general. In some cases, it might be challenging to close the harvest gaps due to limited water availability. Storing water in the rainy season for use in the dry season or collecting water in non-irrigated areas for use in irrigated areas might counteract this issue. Rainwater harvesting and storage in small reservoirs might be an economically viable and flexible solution (Wisser et al., 2010). However, reservoirs lose water by evaporation and, thereby, alter the flow regime and adversely affect freshwater ecosystems. This has to be accounted for when siting and designing reservoirs (Scherer and Pfister, 2016c).

The diets in developed nations are transitioning towards food containing more sugar, salt and saturated animal fats – giving rise to obesity and chronic diseases (Kearney, 2010). In contrast, the reduced consumption of alcohol, tobacco, and animal products – as assumed here for the abandonment of luxury crops can contribute to better health. Note that a complete abstinence from animal products would require further dietary changes, such as an increased consumption of soya, algae, and green leafy vegetables to replace some of the nutrients commonly obtained from animal products (Craig, 2009). However, the changes suggested in this study still allow for consumption of animal products from grazing animals and, as such, only require a reduction.

5. Conclusions

The study shows that sustainable intensification is not an oxymoron. We showed that it is possible to achieve both intensification and improved sustainability simultaneously at a continental scale. We identified high opportunities for sustainable intensification, considering both the society and the environment, on 34% of the arable area in the European countries under investigation. The highest opportunities are found in France, Italy, and Denmark. The largest environmental opportunities exist in terms of harvest gaps, which could be closed by multiple cropping, but must be combined with water storage where water scarcity prevails. By using a set of four sustainable intensification measures (multiple cropping, no-till farming, deficit irrigation, and the abandonment of luxury crop cultivation) at continental scale, it was possible to save land, water, and soil resources, while increasing food security in terms of calorie provision.

Countries with similar socio-economic characteristics might be steered towards sustainable intensification with similar interventions. The study demonstrates the potential of sustainable intensification and gives rise to optimism. At the same time, the study points to areas of interest for more detailed studies that could try to fill some of the remaining research gaps, such as the role of social networks and institutional support for the adoption of sustainable intensification, and a wider coverage of environmental threats and sustainable intensification measures.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2017.11.009.

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